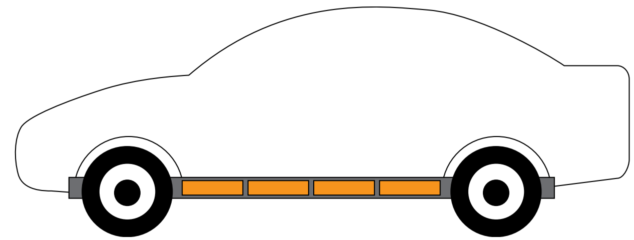
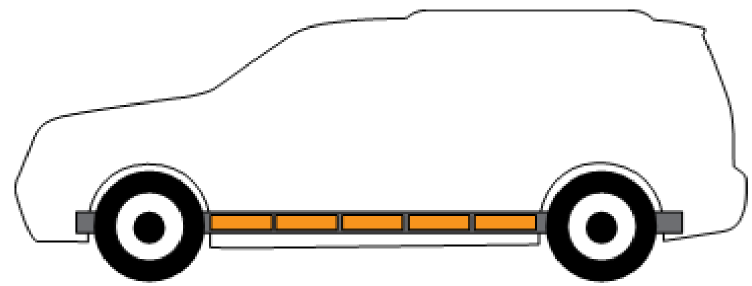
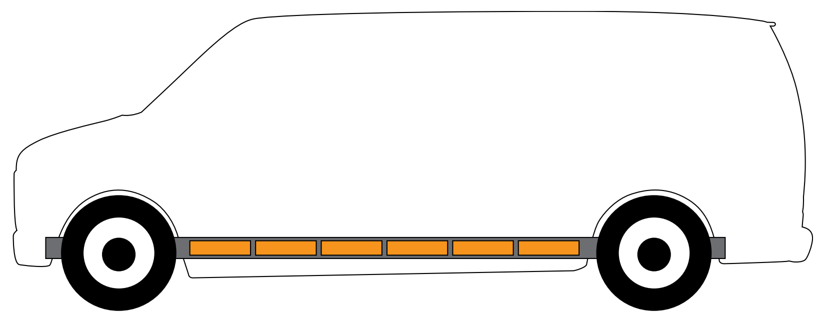
Electric Drive Technologies Overview







Susan Rogers, Technology Development Manager

June 19, 2018

EDT Approach and Strategy

Today
- Market Awareness
- Sustainable Competitiveness

Future
- Goals & Objectives

Research
- Early Stage Focus and Priorities
- Program Roles

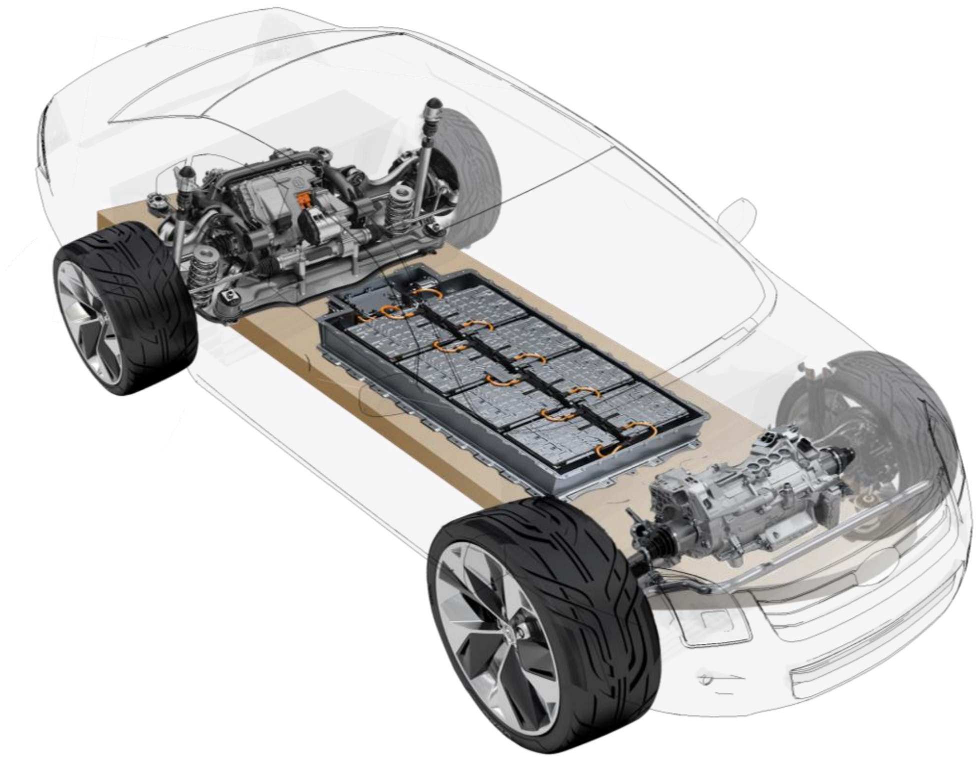
Conclusion
- Direction
- Summary

Market Awareness

Current trends in electric vehicle (EV) architectures and applications:

- OEMs are moving to skate board and/or dedicated architectures for EVs
- Vehicle applications and platforms are expanding (small & large vehicles)
- PHEV (50 miles) and EV range (250+ miles) is increasing
- Faster, high power charging (350+ kW) is essential

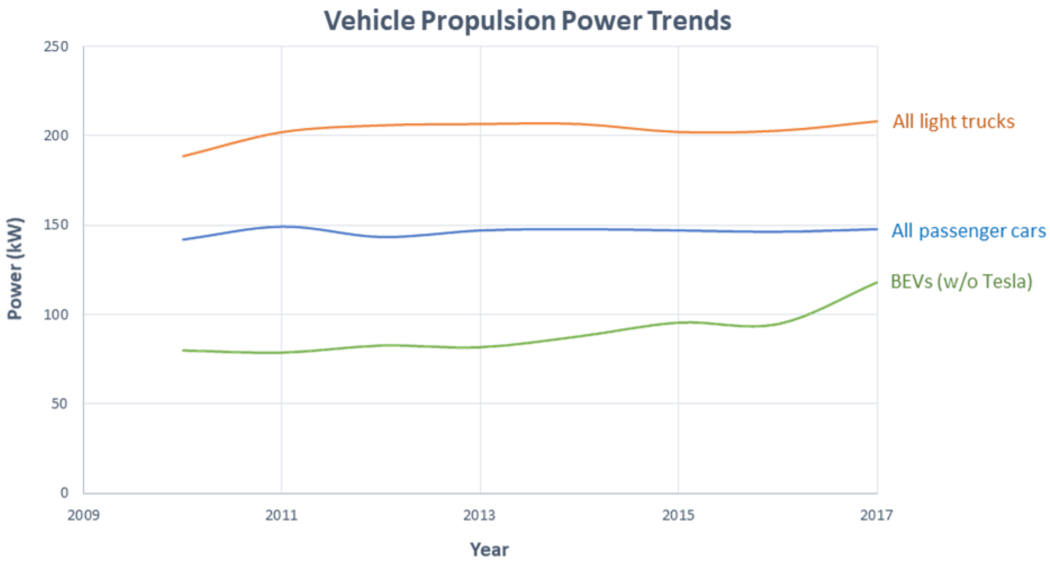
➔Result: Higher vehicle voltages >600V



Market Awareness

Issues and challenges

- Significantly higher power levels:
  - Higher power level systems are needed for broader range of vehicle applications
- Limited space:
  - PHEVs need electric and internal combustion propulsion systems packaged within the existing allocated vehicle propulsion space
- High costs:
  - current technologies are too expensive for mass market adoption



Very limited space under the hood of 2018 Honda Accord PHEV

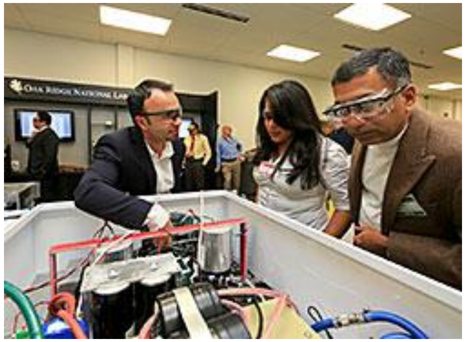
Source: Energetics

Sustainable Domestic Competitiveness

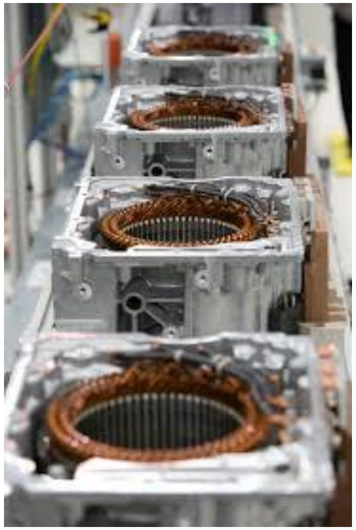
Necessary elements to have and maintain leadership:

- Early stage research to provide leading edge knowledge and enable new solutions
  - Technology innovations
- Applications knowledge to institutionalize technology
  - Basic design, packaging, and manufacturing
- Mass market competitiveness
  - Low margin and high volume

Leadership is only sustainable if industry can master all elements!



National Laboratory Research (Source: ORNL)



Electric Motor Serial Production (Source: GM)

Goals & Objectives

<u>Mission</u>

Accelerate the innovation of electric drive technologies to enable a large market penetration of electric drive vehicles

<u>2025 Goal</u>

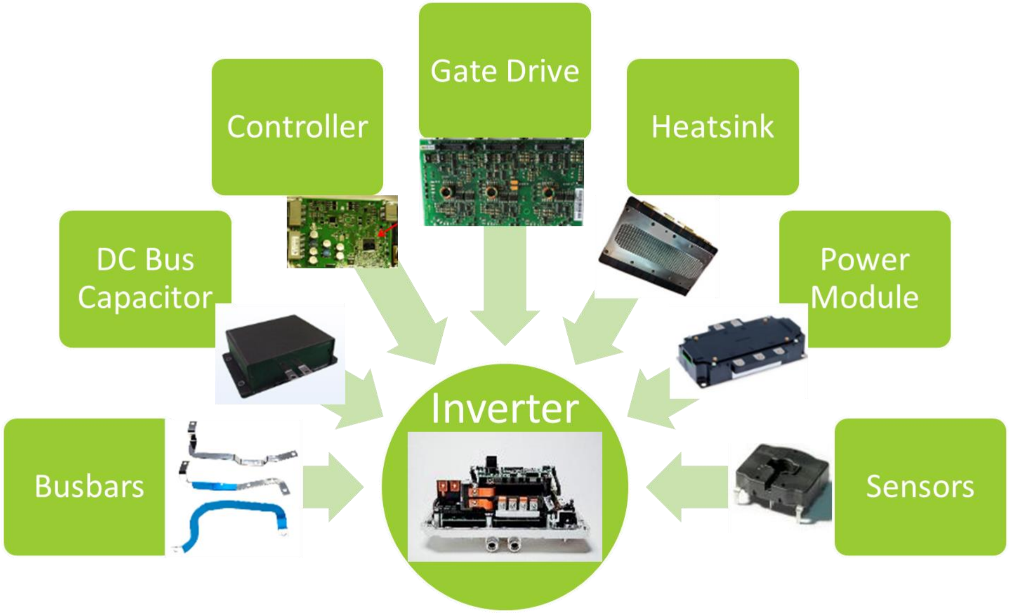
A 100 kW electric traction drive system at 1/2 the cost ($6/kW), 1/10 the volume (33 kW/L), and 2X useful life (300,000 miles) compared to 2015 baseline

2025 Targets (versus 2015)	
Cost	**$6/kW** (50% reduction)
Power Density	**33 kW/L** (843% increase)
Power Level	**100 kW** (100% increase)
Reliability/Lifetime	**300,000 miles** (100% increase)

Power Electronics Priorities for 2025

- Deconstruction of traditional component boundaries enables simplification
- Component integration
- Circuit board-based 3D packaging
- Additional feature integration
- Device application
  - Full automotive operating range characteristics
  - Optimal operating strategies
- In board device fabrication

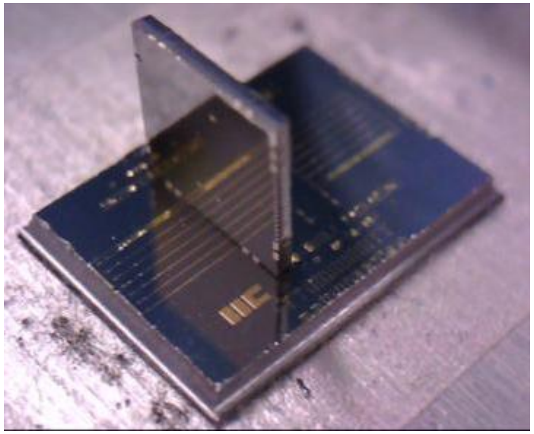
Inverter
$2.7/kW @ 100 kW/L

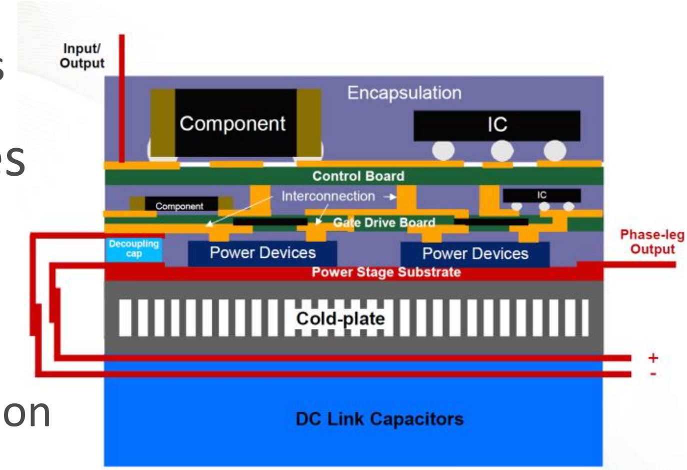


EDT Power Electronics Research

Miniaturization of power electronics to enable wider vehicle applications while reducing cost

- Development of board-based power electronics
  - Planar construction
  - Integration of bus structure, capacitor, and module substrate
  - Gate drives, power modules, and thermal systems
- Full utilization of emerging device capabilities
  - Decrease design margins and increase reliability
  - Ultra conducting copper is a key enabler
  - High performance computing accelerates innovation





Cross-sectional View of a Conceptual Multi-board Stacking Packaging of Automotive Inverter

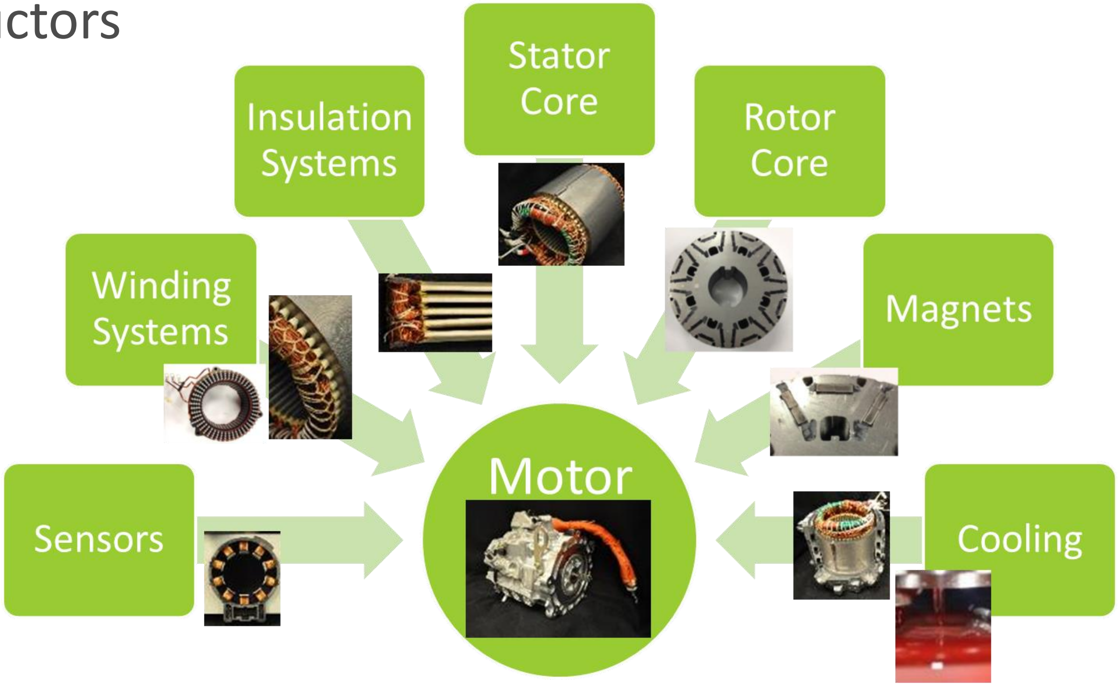
Result: One liter 100kW inverter at a cost of $270 by 2025

Electric Motor Priorities for 2025

Materials innovations and understanding of application improvements

- Electrical steels for higher efficiency
- Nanocarbon-based conductors
- Non-RE magnets
- Soft magnet materials

Electric Drive Motor
$3.3/kW @ 50 kW/L

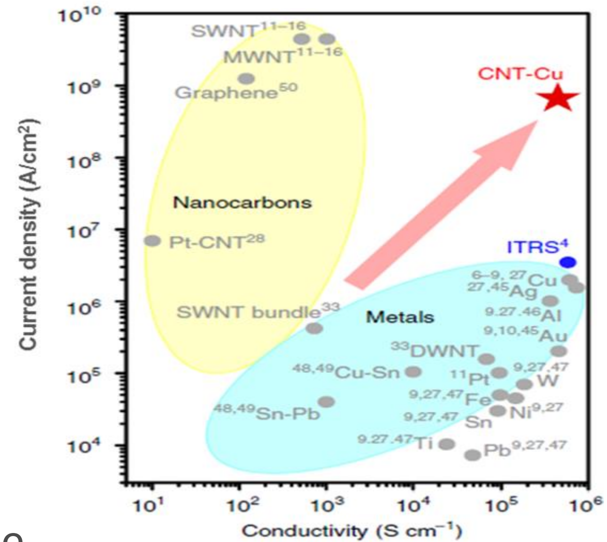


EDT Electric Motor Research

Reduce cost by utilizing fundamentally new materials

- Improved capabilities and performance
  - Electrical steels
  - Ultra conducting copper
  - Heavy rare earth free magnets
  - Low cost, high voltage insulating materials
- Application in motor design innovations
  - Understand new material properties and their use
  - 30-50% improvement in electrical and thermal conductivity
  - High performance computing for more accurate modeling and optimization

International Annealed Copper Standard (IACS): Conductivity of Cu (20° C, 5.8×10^7 S/m = 100%)



C. Subramaniam, *et. al.*, Nat. Commun. (2013)

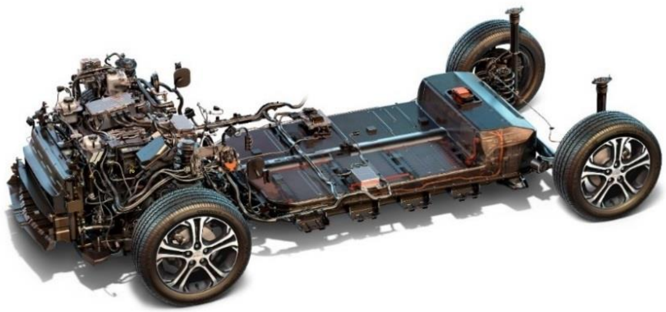
Result: <14 liter 100kW motor @ $330 by 2025

2025 EDT Cost Walk Strategy

Power Electronic Cost Reduction	**Goal** ($330 @100 kW)
Multi Physics Integration	Board based design
Gate Drive & Control Device Improvement	Chip set component reduction and functional improvement for WBG
WBG Device Application w/Full Utilization	Understanding of component drivers of failure and application profiles
High Frequency Operation	Control strategy for higher motor efficiency and reduced passive components
Imbedded Current Sensor	Board based fabricated current sensor
Total Unit Savings	$259

Electric Motor Cost Reduction	**Goal** ($270 @100 kW)
Gen 1, then Gen 2 Covetic Steel and Ultra Copper	Development of new steel and copper
Atomic Level Understanding of Electrical Steel	Characterization Method for Electrical Steel provides understanding at atomic level
Heavy Rare Earth Free Magnets	Development of Heavy Rare Earth Free Magnets
Elimination of Magnets	Development of alternative motor
Total Unit Savings	$114

Roadmap defines the pathway to 2025 targets



Chevrolet Bolt

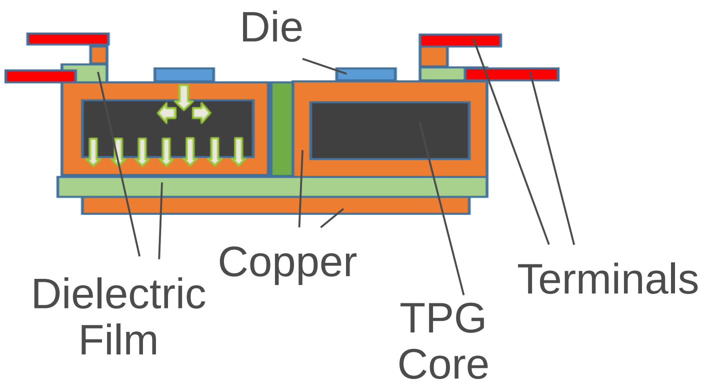
Future Mobility Design Concept

2025 Targets (versus 2015)	
Cost ($/kW)	50% reduction
Power Density (kW/L)	843% increase
Power Level	100% increase
Reliability/lifetime	100% increase

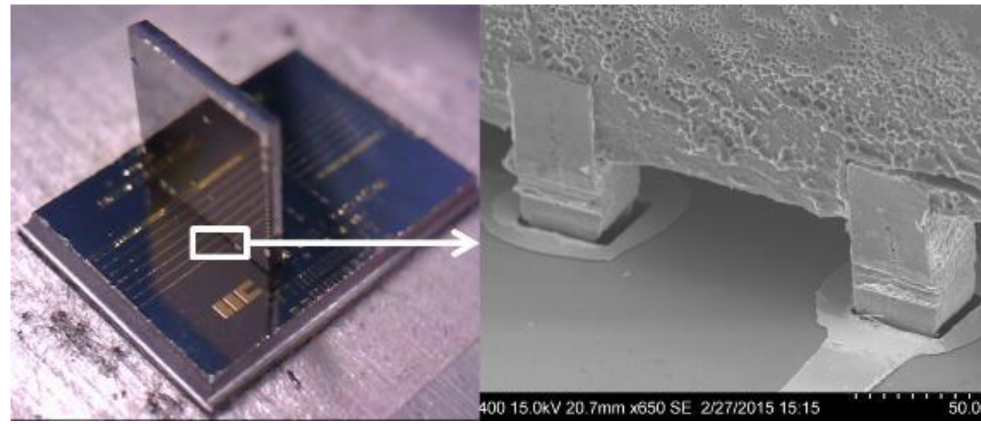
EDT Project Highlights

Advanced Multiphysics Integration Technologies (ELT079)

New substrates and interconnects for high power density

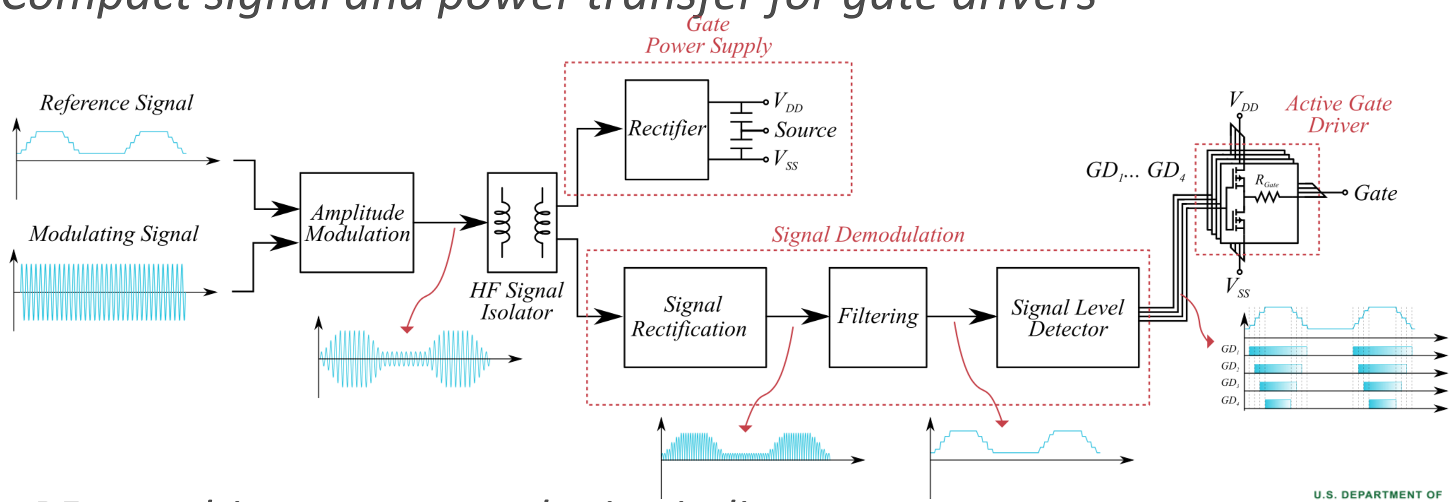


Source: Momentive



Source: Indiana IC

Compact signal and power transfer for gate drivers



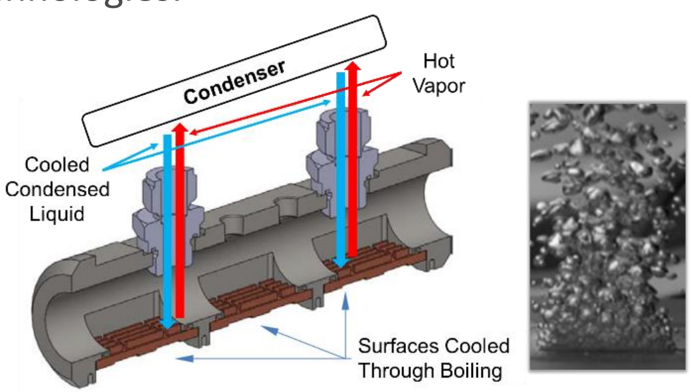
RF gate driver power supply circuit diagram

Source: ORNL

EDT Project Highlights

Power Electronics Thermal Management (ELT078)

- Self-contained passive two-phase system enables high power density without conventional water-ethylene glycol (WEG) liquid cooling. Eliminates hoses, pumps and WEG coolant leaks.
- Research focuses on technologies for compact passive boiling below critical heat flux and compact modular condenser technologies.

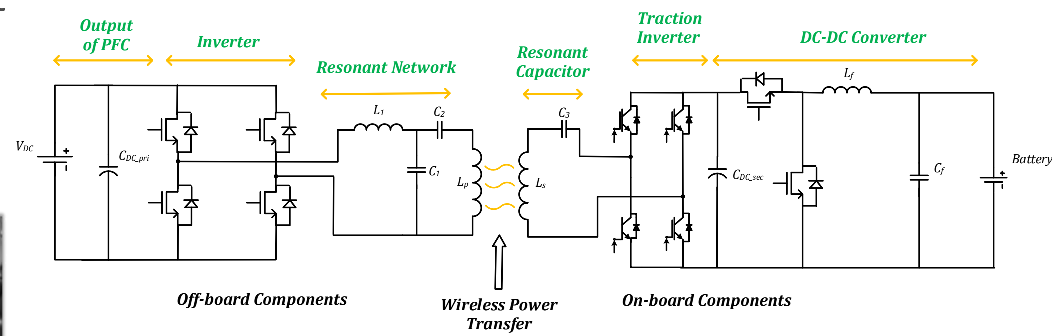


Source: NREL and John Deere

Illustration of example cross-sectional view of the evaporator vessel showing flow of two-phase fluid

Innovative Chargers and Converters (ELT077)

Integrated wireless charger; wireless charging capability with the addition of just a coil and a resonant network, utilizing the traction inverter.



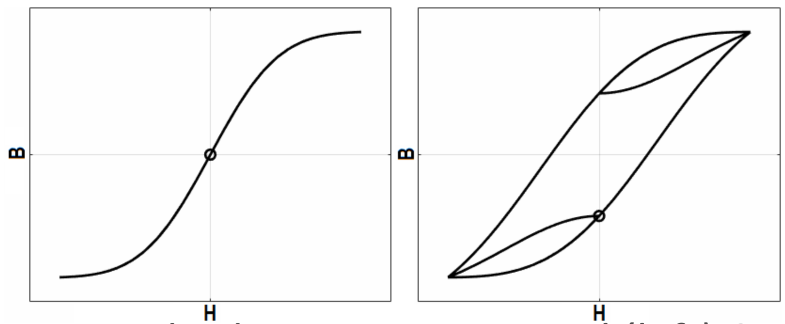
Source: ORNL

Integrated wireless charger circuit diagram

EDT Project Highlights

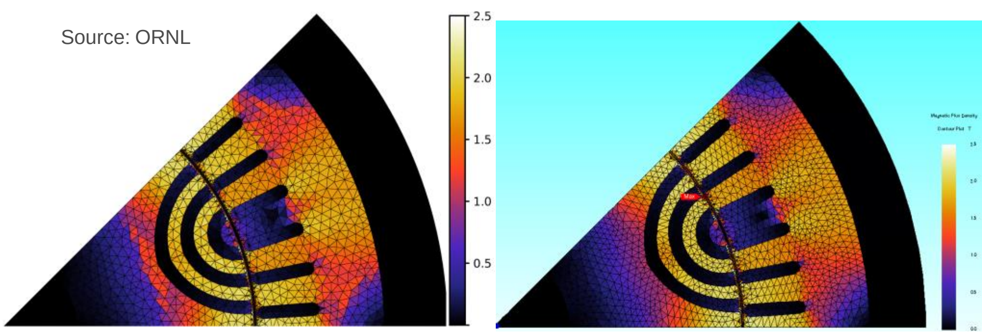
Advanced HPC Modeling of Motors and Materials (ELT049)

Improve motor modeling fidelity and facilitate optimization on HPC systems



Standard magnetic material (left) & improved model (right)

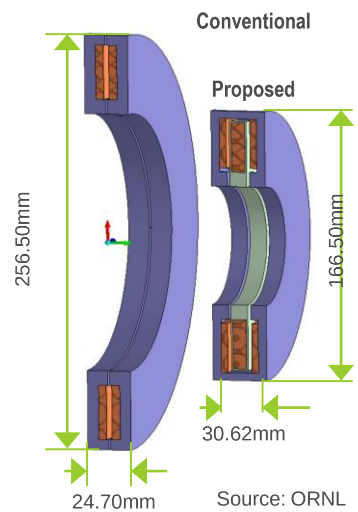
Source: ORNL



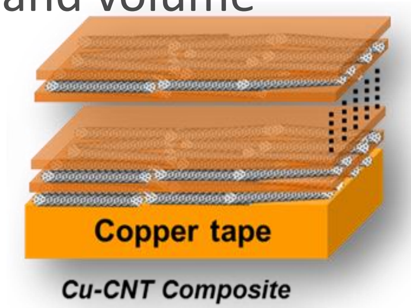
Magnetic flux density of a synchronous reluctance motor simulated using OeRSTED (left) and commercially available software (right)

Non-Rare Earth Electric Motors and Ultra Conducting Copper (ELT074)

- Rotary transformers for wound rotor synchronous motors
- Reduction in mass and volume with UCC



Rotary Transformer Concept



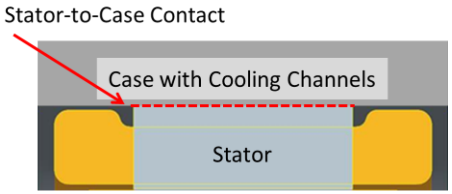
UCC composite

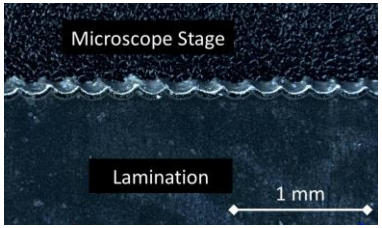
	Cu	CNT
Electrical Conductivity (MS/m)	59.6	100
Thermal Conductivity (W/m-K)	400	4000 W/m-K
Current Density (A/cm^2)	10^6	10^8

EDT Project Highlights

Electric Motor Thermal Management (ELT075)

- Produced data and physics-based model for stator-to-case thermal resistance.
- Collaboration to improve accuracy and prediction of electric motor performance with less product development time and cost.
- Published results improve access to data and tools for motor designs with increased power density without having to resort to overly conservative estimates.



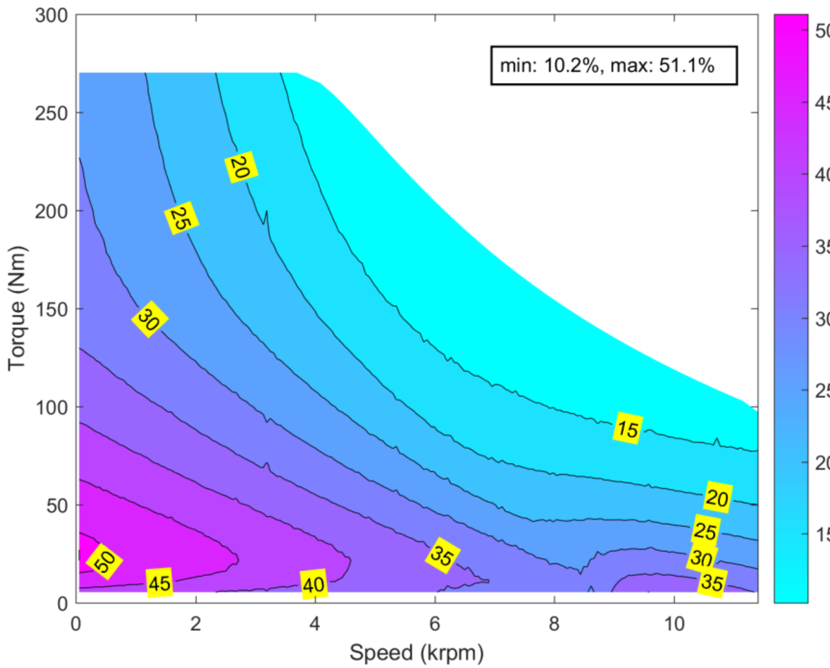


Source: NREL and UQM Technologies

Cross-section view highlighting a stator-to-case interface and edge view of one sample lamination showing a serrated edge

Drivetrain Performance Improvement Techniques (ELT054)

Improve efficiencies in the low efficiency regions of operation by varying the modulation schemes



Source: ORNL

BMW i3 efficiency improvement potential

Government Partnering with Industry

USDRIVE

DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Partners:

21st CENTURY TRUCK PARTNERSHIP

INDUSTRY PARTNERS

GOVERNMENT PARTNERS

Summary

- Market awareness: radical change has and still is occurring moving to dedicated, flexible, electrified skateboard architecture
  – Power density and cost are critical success factors
- Industrial competitiveness factors (R&D, application knowledge, mass production ability) need to be considered to ensure success
- Key elements of EDT R&D to reach 2025 targets
  – Deconstruction of traditional component boundaries and simplification of design
  – Improvements of existing and application of new materials

Description	2025 Targets (100kW System)	
	Cost	Volume
Power Electronics	$2.70/kW	100 kW/ℓ
Electric Motor	$3.30/kW	50 kW/ℓ
Electric Traction Drive	$6.00/kW	33 kW/ℓ

Information Sources

- FY 2017 Advanced Power Electronics and Electric Motors Annual Progress Report:
  - https://www.energy.gov/sites/prod/files/2018/05/f51/Electrification_FY2017_APR_Final.pdf

- Electrical and Electronics Technical Team Roadmap:
  - https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf

- 2017 U.S. DRIVE Highlights of Technical Accomplishments Report:
  - http://www.uscar.org/commands/files_download.php?files_id=476

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https://www.energy.gov/eere/vehicles/vehicle-technologies-office-electric-drive-systems